The procedure for the measurement of incidence angle effects is described in the IEC 61853-2 [1] standard, that was developed under consideration of experiences gained during the Photoclass project. Further information on angle of incidence (AOI) measurements, especially the effect of encapsulation and angular dependence of the spectral responsivity can be found in [2, 3, 4].

This good practice guide should be considered as additional information to the IEC 61853-2 standard.

Requirements for the apparatus IEC 61853-2 - 7.2.2:

- 7.2.2c): "*The spatial uniformity requirements (class B, <5%) shall be fulfilled in the volume that is covered by the active element(s) within the module during rotation. The area of influence should maintain class C (<10%)*". According to [4] these requirements cannot be met for full size modules or even substring using state of the art solar simulators. As a conclusion, solar simulator based measurements can only be performed on cell level. These can be done by using a) Mini-Modules with only one active cell b) separate contacting of one cell through the backsheet, c) partial shading described in [4]. A measurement uncertainty analysis for the impact of spatial non-uniformity on AOI measurements of a solar cell level can be found in [3]. There it is shown that a volume non-uniformity of 7% leads to a measurement uncertainty of <0.5% for a typical industrial solar cell.
- 7.2.2c): "*The solid angle of the light of the simulator should not vary by more than 1° over the active area of the test device.*" According to [4] these requirements cannot be met for 6" cells using state of the art solar simulators with measurement distances up to 7m, that have expanded light sources as light engines ($d_{\text{light source}}$≈25cm). This leads to measurement uncertainties, since the measurement at given incident angle θ_i corresponds to the average angular responsivity of the solar cell for the angular range $\theta_i \pm \Delta\theta$. Since the angular responsivity is an asymmetric function this effect leads to a systematic deviation. A measurement uncertainty analysis for the impact of an expanded light source on AOI measurements of a solar cell level can be found in [3].
- 7.2.2f): "…*accurately positioning the module at the specified angles of incidences to an accuracy of ±1 °.*" This requirement can be considered to be to low, since a systematic offset of the angle of incidence can lead to large measurement uncertainties, e.g. a measurement of the angular responsivity of a solar cell with perfect cosine behavior at AOI=81° instead of AOI=80° would lead to an error of 10%.

$$\frac{\mathrm{Cos}(80° + 1°)}{\mathrm{Cos}(80°)} = 0.9$$

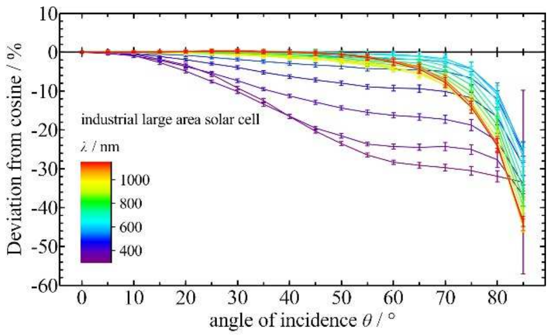
  Hence accuracy of the AOI angle can be considered to be crucial. Under the assumption of symmetrical behavior such a systematic deviation could be identified and hence corrected for if measurements are taken from -80° - 80° (see 7.2.4f).

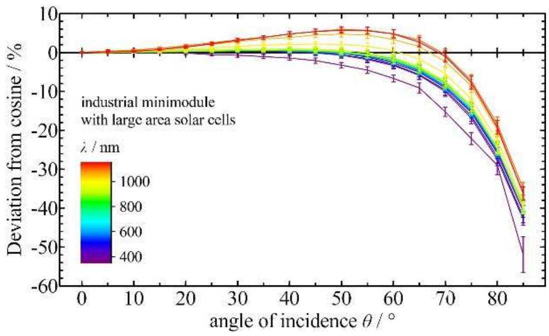
Interpolation of angular transmission IEC 61853-2 - 7.4:

- The formula for deriving the parameter a_r might not be suitable for all photovoltaic devices, since this formula does not allow a relative light transmission >1. A relative light transmission >1 can occur (and was measured [3]) for encapsulated devices such as mini-modules and reference solar cells, where the encapsulant leads to interreflections at higher AOI and hence to a larger area of influence.

Additional remarks:

- Polarization effects: The relative transmission of the PV device can generally be expected to be dependent on the polarization of the incident light [2,3]. Hence, a statement on the polarization of the light source used for the AOI measurements should be mentioned in the measurement report.
- Spectral effects: The relative transmission of the PV device can generally be expected to be wavelength dependent [2,3]. Hence, the spectral responsivity can be expected to be dependent on AOI (see figure below). This leads to the conclusion, that general an angular dependent spectral mismatch corrected should be applied, if the spectral irradiance of the light source differs from the AM1.5 spectrum. However, the angular dependent spectral responsivity is general not known, therefore a measurement uncertainty based on an estimate for this effect should be considered. Exemplary data sets for angular dependent spectral responsivity were generated within the Photoclass project.





The major uncertainty contributions for an AOI measurement are:

- *Electrical non-linearities of the current measurement:* Since the current of the DUT changes by 1 order of magnitude, the non-linearity of the measurement electronics (amplifiers, multimeter,..) should be considered within the uncertainty budget.
- *Over illumination of sample:* The monochromatic light field should be larger than the active area of the solar cell. This includes encapsulation materials, since light transmission and reflection characteristics of encapsulation material are essential for AOI measurements.
- *Monitor principle:* Since the DUT is subsequently measured at different angles, a drift of the irradiance over that period should be corrected for.
- *Reproducibility:* The reproducibility is a key uncertainty contribution. The non-uniformity of the light field should be reproducible to a high degree for AOI dependent measurements.
- *Temperature:* The DUT should be stabilized with respect to the set temperature. Deviation from the set temperature should be corrected for and/or considered in the uncertainties.
- *Irradiance non-uniformity within the rotation volume:* The effect of the non-uniformity on the AOI measurements should be evaluated and considered as measurement uncertainties.
- *Positioning of the device under test relative to the rotational axes*: The positioning of the DUT relative to the rotational axes should be done with great care. In order to evaluate measurement uncertainties related to alignment errors, a sensitivity analysis can be done

by performing AOI measurement with defined misalignment. Especially the exact location of the solar cell within the encapsulant is a crucial parameter.

- *Uncertainty of the tilt angle θ*: This contribution can be considered as crucial. The requirement on the light source (exact parallel light or point source in case of divergent light) should be optimized. Systematic offsets of the tilt angle should be avoided (see above)
- *Spectral and polarization effects:* Angular dependent spectral responsivity and polarization dependent AOI effects should be considered. However, the quantification of such effects is currently beyond state of the art. Hence, even estimates for measurement uncertainties are difficult.

[1] IEC 61853-2:2016, Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral responsivity, incidence angle and module operating temperature measurements (2016)

[2] Geisemeyer, I., Tucher, N., Müller, B., Steinkemper, H., Hohl-Ebinger, J., Schubert, M.C., Warta, W., Angle Dependence of Solar Cells and Modules: The Role of Cell Texturization, IEEE Journal of Photovoltaics, Vol. 7, Issue 1, pp. 19 24, DOI: 10.1109/JPHOTOV.2016.2614120, (2016).

[3] Plag, F, Kröger, I, Fey, T, Witt, F and Winter, S, Angular dependent spectral responsivity - traceable measurements on optical losses in PV devices, Progress in Photovoltaics, *accepted for publication*

[4] Herrmann, W., Schweiger, M. and Rimmelspacher L., Solar Simulator Measurement Procedures for Determination of the Angular Characteristic of PV Modules, Proceedings of 29th EU PVSEC, pp. 2403 – 2406, DOI: 10.4229/EUPVSEC20142014-5CO.16.2, Amsterdam, (2014).